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ENERGY PRICES AND THE ECONOMIC FEASIBILITY OF USING HYDROGEN ENERGY FOR ROAD TRANSPORT IN THE PEOPLE'S REPUBLIC OF CHINA

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Abstract

This study develops quantitative models to conduct economic assessments of the feasibility of producing hydrogen energy from renewable energy and subsequently applying it in the road transport sector in the People's Republic of China. The study applies a well-to-wheel model to analyze the cost of hydrogen as storage for renewable energy, while it uses the total cost of ownership model to analyze the cost and carbon emissions of fuel cell vehicles' (FCEVs') mobility, using the hydrogen produced from renewables as fuel, in comparison with that of alternative vehicle powertrains, especially the conventional fossil fuel-based technology. On such a basis, the study discusses the relationship between the energy prices and the competitiveness of hydrogen produced from renewable energy as well as FCEVs.

Keywords: hydrogen, renewable energy, road transport, the People's Republic of China

JEL Classification: Q21, Q42, Q48, R48

Contents

1. INTRODUCTION

At this moment, hydrogen-related technologies are reaching maturity for commercialization, and the costs are continuously falling due to signs of progress in both technologies and supply chains. The US Department of Energy (DOE) has pointed out that, from 2001 to 2011, the cost of a fuel cell electrolyzer fell by 80% (DOE 2015). Mainstream policy-making institutes and international organizations, such as the US DOE[1] and the International Energy Agency (IEA) (2019), anticipate that hydrogen energy will reach cost parity with conventional energy sources in the long term. Therefore, several countries and regions have announced a roadmap for their hydrogen energy industries as well as their hydrogen energy infrastructure, preparing for the large-scale commercial application of hydrogen (FreedomCAR and Fuel Partnership 2009; Fuel Cells and Hydrogen 2 Joint Undertaking 2019; Hydrogen and Fuel Cell Strategy Council 2019).

The People's Republic of China (PRC) has also started to pay attention to hydrogen energy at policy-making levels in recent years. At the central government level, the State Council announced the "13th Five-Year Plan for the Development of National Strategic Emerging Industries."[2] The National Development and Reform Committee followed this with its announcement of "Advice on Deep Integration and Development of Advanced Manufacturing and Modern Service Industries" in 2019.[3] Both documents highlighted supportive policies and plans for developing hydrogen energy.

At the local government level, several provinces, as well as municipalities, such as Zhangjiakou, Foshan, Rugao, Wuhan, Datong, Suzhou, and Chengdu, have started developing hydrogen energy industrial parks and demonstration projects of hydrogen energy applications. They have already deployed and put into operation more than a thousand units of fuel cell buses and logistics vehicles in these cities as a demonstration and test bedding of the technologies (China Hydrogen Alliance 2018, 2019).

Hydrogen also looks promising as a necessary component of the PRC's future clean energy landscape. Firstly, the large-scale application of renewable energy in the PRC and its concomitant intermittency require a significant energy storage capacity to allow the energy system, such as the power grid, to absorb the renewable energy fully. Otherwise, as is common these days in countries that have already invested heavily in intermittent renewables, abandonment of the harvested renewable energy will happen—a sheer waste of energy and the money invested in the renewable energy capacity. This provides the country with the main motivation to consider hydrogen as massive-scale energy storage.

On the energy storage front, pump hydro, wherever it is still available, is one of the low-cost energy storage solutions. However, most of the development of such potential is already complete. The other solution is large-scale battery storage. However, batteries have many limits, including high capital expenditure (CAPEX) and operational expenditure (OPEX), a short lifetime (5–7 years before scrapping), and fixed and limited

[1] Source: https://www.energy.gov/eere/fuelcells/downloads/fuel-cell-technologies-office-multi-year-research-development-and-22, https://www.energy.gov/eere/fuelcells/doe-technical-targets-hydrogen-production-electrolysis, and https://www.energy.gov/eere/fuelcells/doe-technical-targets-hydrogen-delivery (accessed on 2 December 2019).

[2] Source: http://www.gov.cn/zhengce/content/201612/19/content_5150090.htm (accessed on 2 December 2019).

[3] Source: http://zfxxgk.ndrc.gov.cn/web/iteminfo.jsp?id=16603 (accessed on 2 December 2019).

storage capacity, which continually degrades over their short lifetime. Therefore, as an energy storage option in the power sector, hydrogen is promising, especially considering the scale of abandoned renewable energy in the PRC due to the lack of massive-scale energy storage.

In the meantime, as an energy application in the transport sector, hydrogen has many intrinsic advantages as an energy carrier. First, its energy intensity is higher than that of gasoline: 5 kg of hydrogen carried onboard a sedan vehicle can sustain driving for up to 500 km. Second, refueling can take place as quickly as that of gasoline and diesel. These two advantages make it especially suitable for vehicles undertaking long-distance or heavy-duty trips, such as inter-city buses and trucks delivering cargo.

Third, there are various means of producing hydrogen, especially from clean and indigenous sources, such as renewables, nuclear, biomass, and biofuel. This is critical for the energy security of countries that are highly reliant on imports of fossil fuels to power their transportation sector. Fourth, hydrogen is complementary to the PRC's move to electrify its land transport sector, which currently relies mostly on chemical batteries, such as lead-acid and lithium compound batteries. In this sense, hydrogen provides a complementary solution the coupling of renewable energy and transport. This is especially the case as hydrogen provides a long-term option, such as seasonal storage for renewable energy.

However, in the Chinese context, the literature lacks an understanding of the economics of the hydrogen energy supply and its downstream applications, especially concerning the various combinations of production, transportation, storage, and delivery pathways as well as their applications in different local scenarios with different energy endowments, spatial structures of the market, and users' patterns of usage and preferences. It is also necessary to quantify the implications of various policies, such as subsidies, tax credits, and carbon emission benefits, to give clear signals to both potential investors of hydrogen infrastructure and policy makers.

This study develops quantitative models to conduct economic assessments of the feasibility of producing hydrogen energy from renewable energy and subsequently applying it in the road transport sector in the PRC. It applies a well-to-wheel (WTW) model to analyze the cost of hydrogen as storage for renewable energy, while it uses the total cost of ownership (TCO) model to analyze the cost of fuel cell vehicles' (FCEVs') mobility, using the hydrogen produced from renewables as fuel, in comparison with that of alternative vehicle powertrains, especially the conventional fossil fuel-based technology. Specifically, the study customizes these models for application scenarios in the context of the PRC in terms of energy prices, the power generation mix, the power transmission and distribution system, the pattern of energy demand, the pattern of vehicle usage, taxation, and subsidies.

The WTW model provides estimations of the cost of hydrogen delivered at the refilling stations in \$/kg of H_2 as well as the carbon emissions of FCEVs in kg of CO_2/km. The TCO model gives estimations of the cost of owning and using FCEVs in \$/km. A rich body of literature, such as Pereira and Coelho's (2013) study, has addressed the life cycle analysis of energy consumption and carbon emissions of hydrogen supply pathways. Since one of the most imminent policy issues in the PRC is how to absorb the massive curtailment of renewable energy, especially that from wind, solar, and sometimes even hydropower, our study contributes to the literature and addresses the policy issue by focusing on the production of hydrogen from curtailed renewable energy in the PRC. Therefore, the "well" part of our study starts with the curtailed renewable electricity rather than the construction of renewable energy farms.

The TCO model mainly aims to address the policy issue of the size of the gap between users' costs of FCEVs with hydrogen sourced from curtailed renewables and those of alternative powertrain technologies, such as battery electric vehicles (BEVs), plug-in hybrid vehicles (PHEVs), and internal combustion engine vehicles (ICEVs). It therefore directly reflects the extent to which the government should provide subsidies, tax recessions, or other incentives for the use of FCEVs at the current stage of development of this technology. Moreover, it is possible to extend the scope of the discussion to the externalities or the social cost of FCEVs compared with other types of vehicles by applying a benchmark cost of carbon emissions.

This study delivers the following key findings. (1) Hydrogen as energy storage for renewable energy in the Chinese power sector is not economically competitive yet. Partially this is due to the regulated pricing of electricity in the PRC. (2) Hydrogen as a fuel for passenger fuel cell vehicles is already competitive due to the substantial subsidies that the government currently provides. (3) However, this is not the case regarding fuel cell buses and trucks. More support for the R&D of both these technologies might be important to reduce their CAPEX meaningfully. (4) Additional fuel taxes on conventional fossil fuel, carbon tax, and carbon emission trading could also significantly improve the competitiveness of clean or zero-emission hydrogen energy.

The rest of the paper proceeds as follows. Section 2 contains a literature review. Section 3 presents the methodology and data. Section 4 discusses the findings from our modeling analysis. Finally, section 5 concludes and draws policy implications.

2. LITERATURE REVIEW

The study reports the literature review in three subsections: 1—upstream: hydrogen production; 2—mid-stream: transportation and delivery of hydrogen; and 3—downstream: applications of hydrogen as energy.

2.1 Upstream: Hydrogen Production

First, at the production stage, especially regarding hydrogen produced from electrolysis, there are two main cost drivers: one is the high capital cost of production equipment, such as electrolyzers; the second is the cost of energy, especially electricity (Rahil 2017). Distinguishing electricity by its sources, the cost of electrolysis using renewable energy could be much higher than that using grid electricity, while the cost of production in distributed hydrogen production is higher than that of centralized large-scale production. The latter comes with a significant economy of scale. Table 1 summarizes the findings regarding the cost of hydrogen production from the literature.

Several international organizations have provided cross-country comparisons of the cost of hydrogen production. The Asia Pacific Energy Research Centre (APERC) (2018) found significant differences in the cost of hydrogen production following various paths. For example, hydrogen production using electricity from solar PV costs USD6.65/kg, 6.02/kg, 4.12/kg, and 3.7/kg in the Republic of Korea, Japan, the PRC, and the US, respectively; hydrogen production using electricity from wind power costs USD6.65/kg, 5.66/kg, 4.21/kg, and 3.99/kg in the Republic of Korea, Japan, the PRC, and the US, respectively. Among all the pathways that use renewables to produce hydrogen, the lowest costs come from hydropower in New Zealand and Canada, at USD2.69/kg and 2.66/kg, respectively. For the production of hydrogen from fossil fuels, the cost of coal gasification with carbon capture and storage (CCS) falls into the range between USD2.27/kg and USD2.61/kg in various countries. Natural gas reforming with CCS has the lowest costs among the fossil fuel pathways, ranging between USD0.78/kg (in the Russian Federation) to USD1.49/kg (in the US).

Table 1: The Estimated Cost of Hydrogen Production from the Recent Literature

	Country/ Region	Energy Source	Type of Technology	Estimated Cost	Expected Future Cost
James, DeSantis, and Saur (2016)	US	Grid electricity	Large-scale centralized; proton exchange membrane (PEM) electrolyzer	USD4.20–5.11/kg	
	US	Grid electricity	Large-scale centralized; solid oxide electrolysis cell (SOEC)	USD3.82–4.96/kg	
	US	Grid electricity	Small-scale on-site; proton exchange membrane (PEM) electrolyzer	USD4.23–5.14/kg	
	US	Grid electricity	Small-scale on-site; molten carbonate fuel cell (MCFC)	USD2.58–3.71/kg	
	US	Biomass	Large-scale centralized; biomass fermentation	USD51/kg	USD5.65/kg (by 2025)
Rahil (2017)	Canada	Medium-scale wind power	On-site electrolysis	USD9.0/kg	
Rahil, Gammon, and Brown (2018)	Libya	Small-scale wind power	On-site electrolysis	GBP9.3–10.4/kg	GBP6.2–6.6/kg (by 2030)
Miller, Raju, and Roy (2017)	US	Natural gas, solar PV, and biomass	Large-scale SMR, electrolysis, and gasification	USD1.89/kg, 6.16/kg, and 2.5/kg, respectively	
	US	Natural gas, grid electricity, and biomass	On-site distributed production	USD2.03/kg, 5.75/kg, and 3.32/kg, respectively	

Source: Authors' summary based on the literature.

The IEA (2019) estimated the cost of hydrogen production through several pathways in the PRC. Hydrogen produced from coal has the lowest cost, at USD1.1/kg; if applying CCS, then the cost increases to USD1.6/kg. Natural gas reforming costs USD1.8/kg, and it increases to USD2.3/kg if applying CCS. Hydrogen produced from electrolysis using renewables costs about USD3.0/kg, while it costs USD5.4/kg if using grid electricity.

2.2 Mid-stream: Transportation and Delivery of Hydrogen

Besides the cost of hydrogen production, the infrastructure and network for the transportation, storage, delivery, and refilling of hydrogen are also costly and to a large extent decide the cost of hydrogen to end-users. Currently, mainstream technologies for the transportation and delivery of hydrogen include pipelines, compressed hydrogen, liquefied hydrogen, and a liquid organic hydrogen carrier (LOHC).

The US Department of Energy (2015) estimated the cost of hydrogen transportation, delivery, and refilling using the HDSAM tool that the Argonne National Laboratory (ANL) developed as follows: (1) pipeline (100 km): USD4.85/kg; (2) compressed hydrogen trailer (283 km): USD3.30/kg; and (3) liquid hydrogen trailer (283 km): USD3.25/kg.

Reuß et al. (2017) estimated the cost of hydrogen transportation and delivery with trans-seasonal storage for 60 days. By mixing the use of compressed hydrogen, liquid hydrogen, and an LOHC for different sections of the supply chain, the costs of transportation and delivery range from 4.5 euro/kg to 6.5/kg. The hydrogen production capacity assumption in this study is 50 tonnes/day, with a transportation and delivery distance of 250 km.

APERC (2018) studied the scenarios of various countries in Asia and the Pacific exporting hydrogen to Japan for subsequent uses in power generation applications and fuel cell electric vehicle (FCEV) applications. In the power generation application scenarios, considering the transportation of hydrogen in liquid form, the costs of transportation from Indonesia, Australia, the US, and the Russian Federation reached USD2.23/kg, 2.51/kg, 2.3/kg, and 1.76/kg, respectively. In the case of FCEV applications, it is necessary to consider the cost of hydrogen refilling stations; therefore, the final cost of hydrogen to the end-user reached USD12.6/kg if the hydrogen came from solar PV-based production in Indonesia. The final user cost of hydrogen reached USD8.28/kg in the case of hydrogen from natural gas reforming in the Russian Federation.

The IEA (2019) studied the case of Australia exporting hydrogen to Japan. The estimated cost of liquid hydrogen transportation is USD3.2/kg. Using an LOHC and ammonia for the transportation of hydrogen could reduce the cost to USD2.2/kg and USD1.6/kg, respectively.

It is thus possible to observe that factors such as the geographical conditions, the distance of transportation, and the choice of transportation technologies result in the cost of transportation and delivery varying significantly among different regions and different countries and in different application scenarios. At this moment, there is a general lack of literature about the cost of hydrogen transportation and delivery in the PRC.

2.3 Downstream: Applications of Hydrogen as Energy

Last but not least, we review the cost matters in the downstream, which involves the application of hydrogen energy, including the power sector, the heat supply, and the transport sector. The key is whether hydrogen energy applications could compete with conventional energy in these sectors. If not, what are the future cost targets for hydrogen energy to become competitive?

The Fuel Cell Technology Office of the US Department of Energy started to make and routinely renew its MYRD&D (Multi-Year Research, Development, and Demonstration) in 2003. According to this office, when meeting the following cost targets, hydrogen energy will become competitive:

A. The total supply cost, namely the cost including the production cost and the cost of transportation and delivery, should be lower than USD4.0/kg, in which the cost of transportation and delivery is lower than USD2.0/kg;

B. The capital cost of the electrolyzer system becomes lower than USD300/kW, while its conversion efficiency reaches as high as 77%;

C. The cost of the fuel cell system becomes lower than USD40/kW by 2020, with peak efficiency reaching 65% and a life expectancy of 5,000 hours. Eventually, the cost of the system reaches USD30/kW, with life expectancy of 8,000 hours.

D. Vehicles’ onboard hydrogen storage reaches as low as USD10/kWh by 2020 and eventually converges to USD8/kWh.

In Japan, as APERC (2018) showed, the total supply cost of hydrogen should be as low as USD1.92/kg–USD3.23/kg to compete with coal-fired power generation.

To compete with power generation using LNG, it needs to reach USD2.04/kg–USD2.64/kg. In the transport sector, it needs to be as low as USD1.32/kg to compete with conventional internal combustion engine vehicles (ICEVs).

Hydrogen Europe (2018), a European hydrogen and fuel cell association affiliated with the European Union, expected the cost of electrolyzer to fall to 720 euro/kW by 2025 so that the cost of hydrogen production by electrolysis reaches 5 euro/kg. After 2030, it expected that large-scale applications of hydrogen technologies could help to reduce the cost of the electrolyzer to as little as 500 euro/kW, therefore reducing the cost of hydrogen production to 3 euro/kg. On the hydrogen storage front, if the capital cost of large-scale hydrogen storage could reach 5 euro/kWh, which is 1/100 of the current cost of battery storage, it will become economically competitive. The capital cost of distributed hydrogen storage should reach 10 euro/kWh. On the transportation and delivery front, there is an expectation that all pathways will reach cost levels lower than 1 euro/kg by 2030. Around the same time, the capital cost of fuel cells will reach 50 euro/kW, so the capital cost of hydrogen storage and fuel cell systems for a passenger vehicle (FCEV) becomes lower than 5,000 euro, while that of a bus becomes lower than 40,000 euro.

In the East Asian region, according to the Economic Research Institute for ASEAN and East Asia (ERIA) (2019), in the power sector, if only considering the cost, insurance, freight (CIF) cost of imported energy, including hydrogen and other types of energy, hydrogen should be as cheap as USD0.53/kg–USD0.85/kg to compete with coal. It needs to reach USD1.29/kg–USD 1.41/kg to compete with natural gas. Regarding the application of hydrogen in the industry sector, taking Japan as an example, hydrogen needs to reach USD1.69/kg–USD1.99/kg to compete with natural gas.

In the transport sector, if only considering the comparison of fuel costs, hydrogen needs to reach USD4.24/kg–USD5.0/kg to compete with conventional ICEVs in Japan. In the case of Indonesia, the competitive range of the hydrogen cost is USD3.78/kg–USD4.53/kg. As Li (2019a) and Li (2019b) further pointed out, according to the ERIA report, considering the high capital cost of FCEVs and the high cost of hydrogen supply together, the per km cost of FCEV usage is twice as high as that of ICEV usage.

Therefore, the study can conclude that, to achieve competitiveness for large-scale commercial application, hydrogen energy needs further efforts from at least three aspects:

1. more continuous investment in RD&D to improve technical performances and reduce costs through technological improvements;
2. prioritization of the development of early markets and niche markets for hydrogen energy applications to benefit from the learning effects, the economy of scale, and the network effect of the hydrogen energy infrastructure and thus reduce costs accordingly; and
3. sufficient and supportive policies that favor the development and adoption of hydrogen energy and fuel cell technologies. In this regard, it is possible to refer to the policies that countries have adopted to support BEVs as examples.

3. METHODOLOGY AND DATA

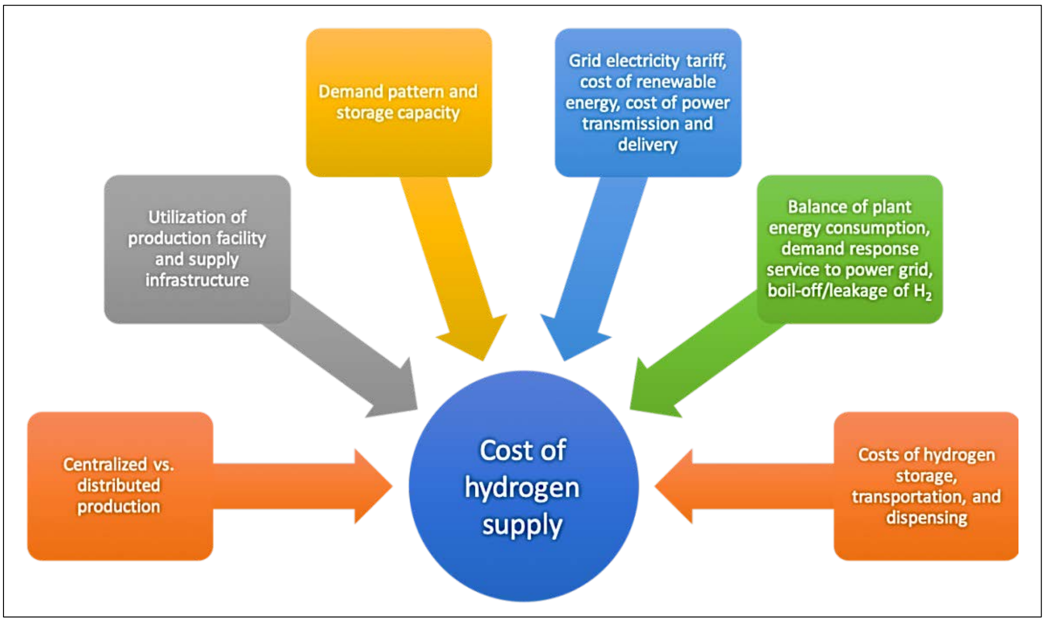
This study aims firstly to investigate the economics of hydrogen produced from renewable energy as an energy application for the road transport sector in the PRC.

Specifically, it will estimate the cost of producing hydrogen from renewable energy, the logistics costs of transporting and storing hydrogen, and eventually the cost of refueling vehicles with hydrogen at the hydrogen station. Then it will compare the application of FCEVs with vehicles with alternative powertrains, such as battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEV)/hybrid electric vehicles (HEVs), and conventional internal combustion engine vehicles (ICEVs).

The study develops WTW cost models, as well as TCO models, covering both the upstream and the downstream of the hydrogen economy, to simulate various scenarios, assuming different technologies and industrial processes of hydrogen production pathways, different energy endowments that determine the mix of hydrogen production and the costs of primary energy inputs, different usages of vehicles in various fleets, and country-specific energy policies, such as taxes, surcharges, and subsidies applied to conventional as well as new energy products and technologies. Scenarios containing reasonable assumptions about the above-mentioned key factors will be able to indicate precisely the economic and commercial feasibility of establishing hydrogen supply chains.

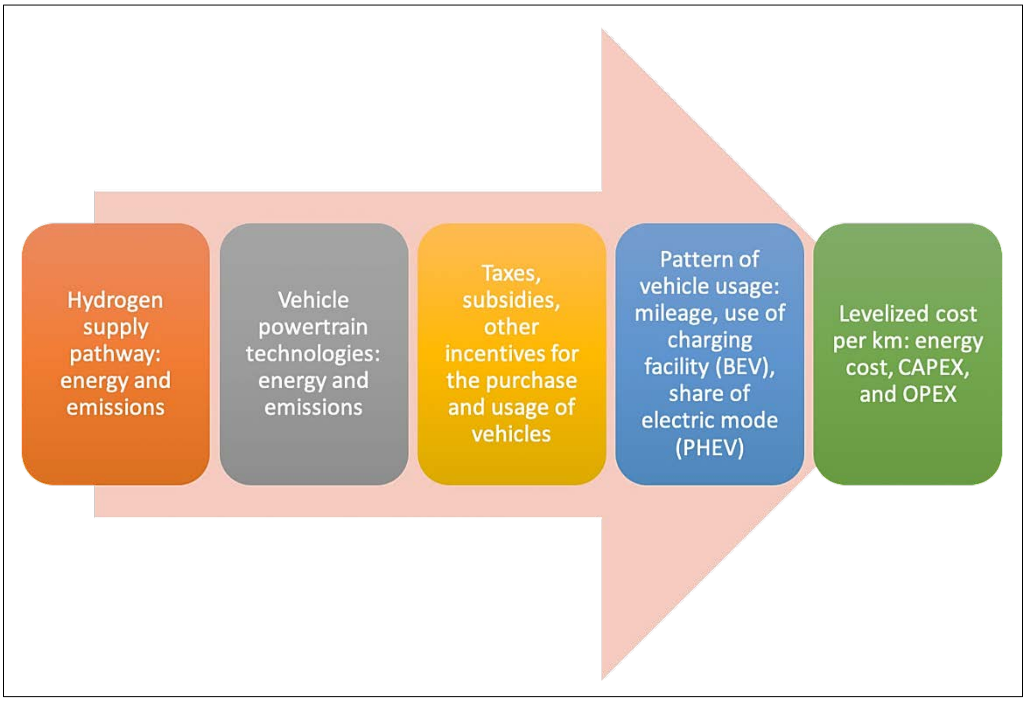
Figure 1 illustrates the key features and factors that a WTW model for the hydrogen supply chain captures. The specification of a hydrogen supply chain starts with the choice of centralized production mode or forecourt production mode. The former requires transport and delivery infrastructure, while the latter involves on-site production at the location of catering. This model considers important features such as the utilization rate, the transport, storage, and delivery pathway, the corresponding capacity and operation of infrastructure, the energy consumption of the supply chain, and the cost of energy inputs.

Figure 1: Key Features and Factors that the WTW Model for the Hydrogen Supply Chain Captures



Source: Authors' depiction.

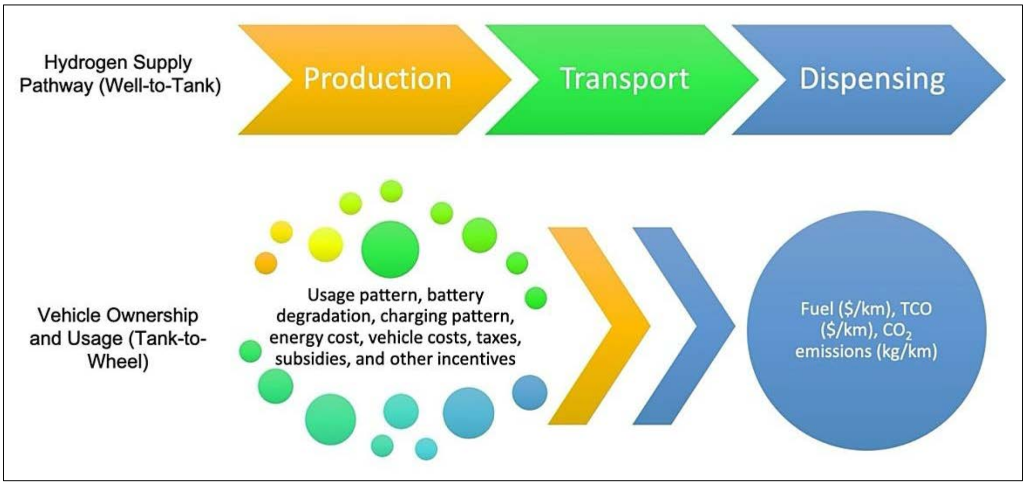
Figure 2: Key Input and Output of a TCO Model for Vehicles



Source: Authors' depiction.

Figure 2 presents the key input and output of a TCO model for FCEVs as well as other competing powertrains. These include the energy and emissions of the production, transport, and delivery of energy to refill the vehicle, the technical parameters of the vehicle, and the pattern of vehicle usage. Eventually, the output includes the levelized cost of owning and driving the vehicle for each km during its expected lifetime based on the estimation of its CAPEX, OPEX, and fuel cost.

Figure 3: Connecting the WTW Model of the Hydrogen Supply Chain and the Vehicle TCO Model



Source: Authors' depiction.

Figure 3 illustrates how our study combines the WTW model of the hydrogen supply chain and the vehicle TCO model. The output of the former supplies the latter as input. As the output, we obtain the TCO cost of the vehicle as well as its implications for emissions.

This study focuses on the impact of energy prices, including those of renewable energy and fossil fuels, as the basic inputs to produce hydrogen as well as to transport and deliver hydrogen. The table below presents our assumptions on the benchmark costs of energy in the PRC.

Table 2: Benchmark Assumptions on Energy Prices in the PRC

	Grid Electricity ($/kWh)	**Solar PV** ($/kWh)	**Wind** ($/kWh)	**Hydropower** ($/kWh)	**Diesel** ($/Liter)	**Gasoline** ($/Liter)	**Heavy Fuel Oil** ($/Tonne)
Prices	0.092	0.029	0.044	0.033	0.9	1.01	455.5

Source: Authors' assumptions.

The prices of renewable energy that we assume here are based on the assumption of the use of curtailed renewable energy for hydrogen production. Table 3 describes the renewable energy curtailment assumptions.

Table 3: Assumptions on Curtailed Renewable Energy

	Solar PV	**Wind**	**Hydropower**
Project scale (MW)	4,000	4,000	4,000
Capacity factor	20%	33%	36%
Curtailment rate	30%	30%	30%
Curtailed energy (MWh)	2,102,400	3,437,434	3,752,784

Source: Authors' assumptions.

To test the sensitivity of the total cost of supplied hydrogen to changes in energy prices, we assume that energy prices vary in a range of –20% to +20% around the benchmark prices. The specification of the FCEV models is as follows (Table 4).

Table 4: Specification of the FCEV Models

	FC Stack Capacity (kW)	**Battery Capacity** (kWh)	**Tank Storage** (kg)	**TTW Efficiency Electric Mode** (MPGe)	**Range of Electric Mileage** (km)	**OMV** ($)
Passenger cars	114.7	1.6	5.0	67.0	482.8	57,500
Buses	228.0	12.0	37.5	6.63	400.0	920,017
Trucks	228.0	12.0	40.0	5.0	321.9	900,000

Source: Authors' compilation based on manufacturers' public reports.

The data on the CAPEX and OPEX of the hydrogen supply chain, including the production, transportation, delivery, and vehicle ownership and usage, are based on various literature, mainly Teichmann, Arlt, and Wasserscheid (2012), Rahil (2017), Reuß et al. (2017), APERC (2018), Demir and Dincer (2018), Rahil et al. (2018), ERIA (2019), Hassan, Patel, and Parra (2019), Parra et al. (2019), and Reuß et al. (2019).

4. RESULTS AND FINDINGS

4.1 TCO Analysis

Firstly, we specify a scenario of transportation and delivery as the domestic medium distance of 100 km from the centralized production site of hydrogen to the hydrogen refilling stations. The transportation and delivery process involves a hydrogen storage facility that has a capacity equivalent to 7 days of the system's maximum hydrogen production.

Accordingly, the study estimates the total cost of hydrogen supplied at the refilling stations, through different transportation and delivery pathways, as follows (Table 5).

Table 5: The Estimated Total Cost of Hydrogen Supplied
($/kg)

	Pipeline	Compressed Hydrogen Truck	Liquid Hydrogen Truck	LOHC Truck
Solar PV	5.67	6.27	19.50	8.06
Wind	6.30	6.96	20.80	8.96
Hydropower	5.74	6.41	19.78	8.24

Source: Authors' calculation.

With such hydrogen prices at the refilling station, Table 6 presents the cost per km of FCEV usage in three-vehicle fleets in the PRC, namely passenger cars, buses, and trucks, using the TCO model and applying hydrogen sourced from solar energy. The TCO in terms of $/km includes the CAPEX, OPEX, and fuel costs.

Table 6: Total Cost of Ownership of FCEVs in the PRC (Hydrogen Sourced from Solar PV)
($/km)

	Pipeline	Compressed Hydrogen Truck	Liquid Hydrogen Truck	LOHC Truck
Passenger Cars	0.295	0.303	0.479	0.327
Buses	3.495	3.576	5.352	3.815
Trucks	3.082	3.189	5.545	3.507

Source: Authors' calculation.

These could be compared with the TCO of vehicles (of a typical and comparable specification, such as engine power) with alternative powertrains, including BEVs, PHEV/HEVs, and ICEVs (Table 7).

Table 7: Total Cost of Ownership of Vehicles with Alternative Powertrains in the PRC
($/km)

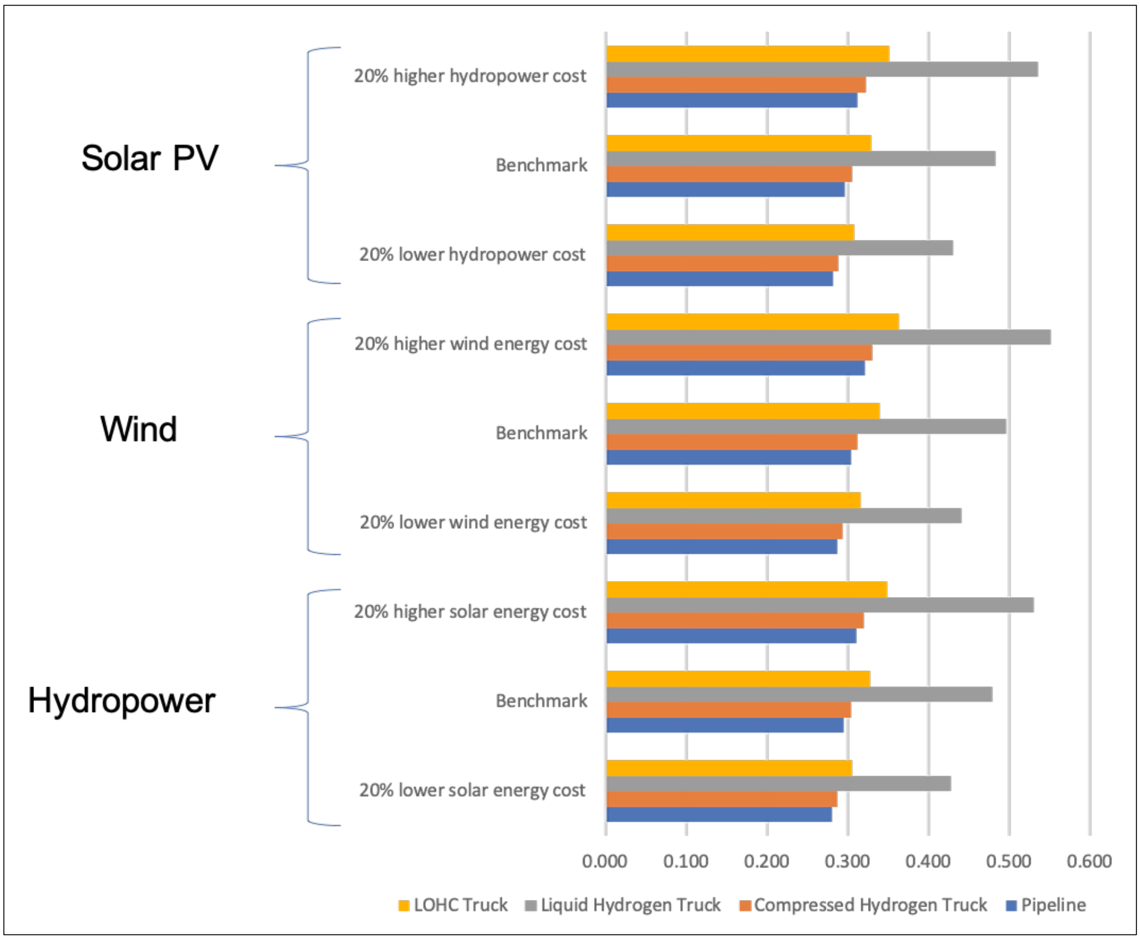
	BEV	PHEV/HEV	ICEV
Passenger Car	0.466	0.561	0.414
Bus	1.607	2.085	1.733
Truck	0.858	0.944	1.017

Source: Authors' calculation.

It is thus observable that, first, FCEVs in general are not competitive against other powertrains, not even BEVs. Second, however, due to the generous subsidies for fuel cell passenger cars that the government announced in 2019, which amount to around $57,000 per vehicle, they already appear to be competitive with other powertrains, including ICEVs. However, these are the subsidies that the Chinese central and local government can offer on a small scale for demonstration purposes. It is highly unlikely that such generous subsidies could continue as fuel cell passenger cars come into large-scale commercial use.

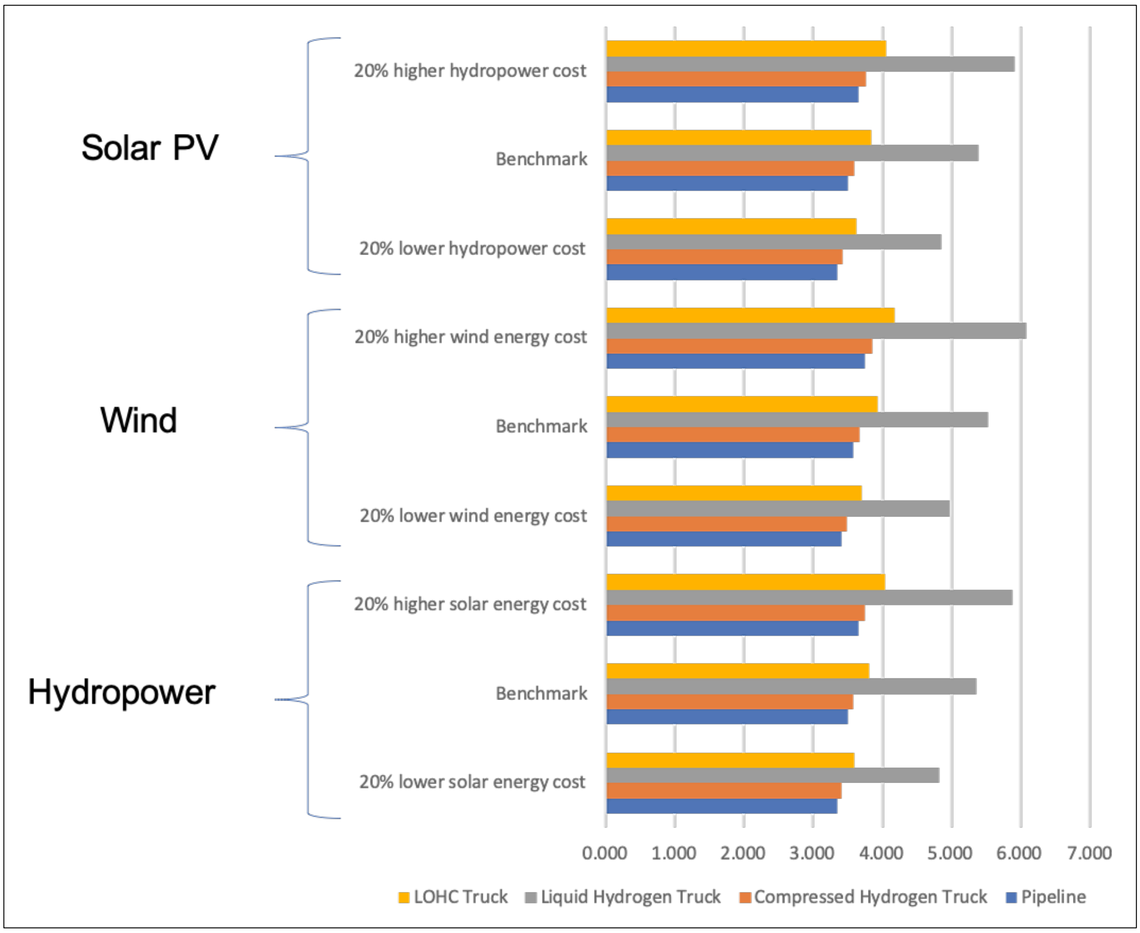
To determine the role played by the fuel cost, namely the total supply cost of hydrogen, we conduct the following sensitivity analysis. Figure 4 presents the comparison of energy cost sensitivity scenarios for passenger cars. Figure 5 presents the comparison for buses and Figure 6 the comparison for trucks.

Figure 4: Hydrogen Cost Sensitivity Scenarios (TCO of Passenger Cars) ($/km)



Source: Authors' calculation.

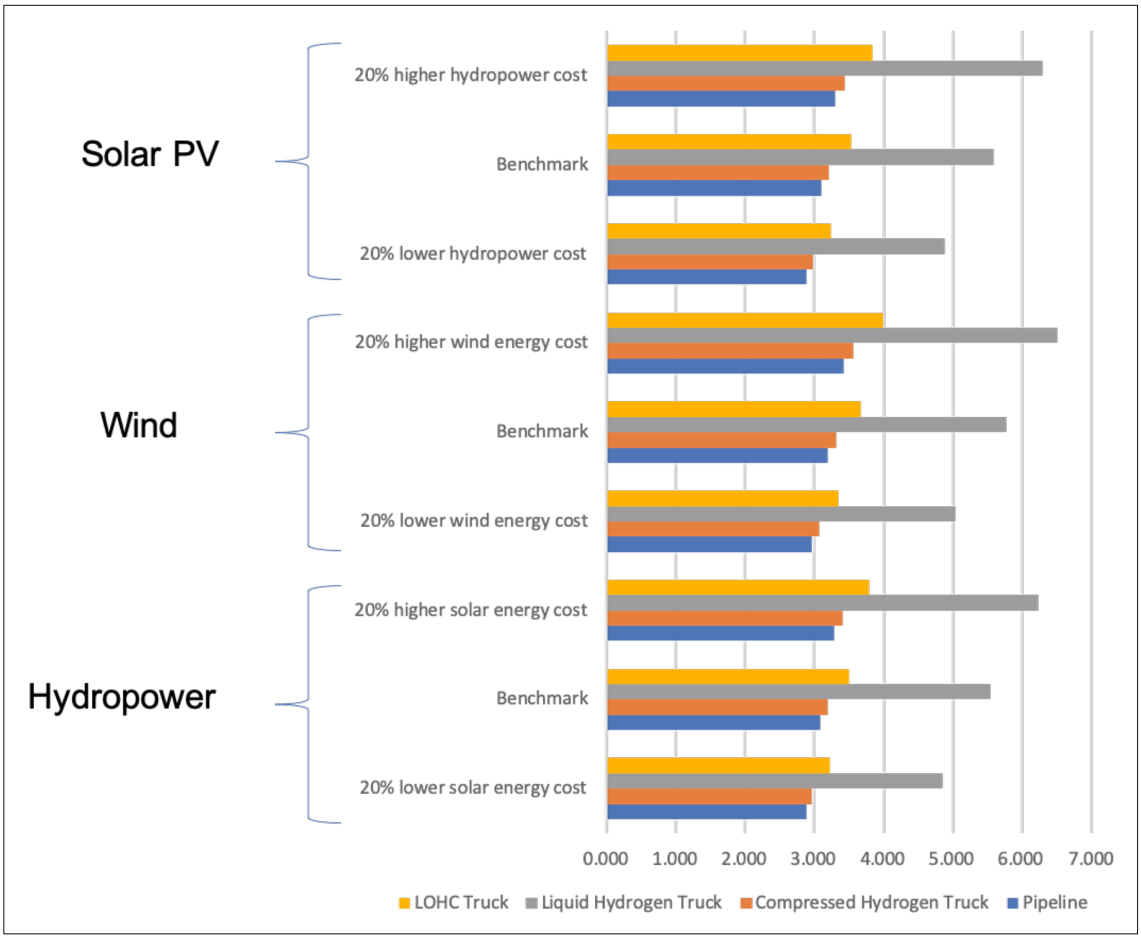
Figure 5: Hydrogen Cost Sensitivity Scenarios (TCO of Buses)
($/km)



Source: Authors' calculation.

It is apparent that, although the variation in hydrogen costs could significantly influence the economic competitiveness of FCEVs, non-fuel costs still determine the majority of the TCO for FCEVs, namely the CAPEX and non-fuel OPEX of the vehicles per se. Therefore, while it is important to make sure that the cost of supplying hydrogen falls substantially in the future, it is even more important that FCEV technologies and related industries make substantial progress in reducing the CAPEX of the vehicles.

Figure 6: Hydrogen Cost Sensitivity Scenarios (TCO of Trucks)
($/km)



Source: Authors' calculation.

4.2 Carbon Emissions of FCEVs

Our WTW model also estimates the carbon dioxide emission levels of road transport vehicles in the three different fleets. Table 8 presents the estimations of the emissions of FCEVs in the case of the PRC, with hydrogen sourced from electricity produced using solar PV. We compare this with the carbon dioxide emission levels of BEVs, PHEVs, and ICEVs in the PRC in Table 9. We estimate the numbers based on common vehicle models available in the market. In the case of BEVs, since it is typically impossible to earmark the electricity that they use as coming from specific clean energy sources, we apply the carbon emissions of grid electricity in the PRC.

Table 8: Carbon Emissions of FCEVs in the Three Fleets
(kg/km)

	Pipeline	Compressed Hydrogen Truck	Liquid Hydrogen Truck	LOHC Truck
Passenger Cars	0.036	0.038	0.118	0.042
Buses	0.344	0.366	1.174	0.406
Trucks	0.457	0.486	1.556	0.538

Source: Authors' calculation.

Table 9: Carbon Emissions of BEVs, PHEVs, and ICEVs in the Three Fleets
(kg/km)

	BEVs	PHEVs	ICEVs
Passenger Cars	0.084	0.149	0.132
Buses	0.714	0.898	1.586
Trucks	0.700	0.937	1.219

Source: Authors' calculation.

Comparing Tables 8 and 9, we can see that, with hydrogen sourced from electricity produced using solar PV, hydrogen supplied through most pathways, such as pipelines, compressed hydrogen, and LOHCs, present the lowest levels of carbon dioxide emissions among all the powertrain technologies. Thus, the concept of FCEVs powered by hydrogen sourced from renewables is indeed a desirable low-carbon emission solution. In the case of liquefied hydrogen, we note that the economies of scale should also be able to play a significant role in driving down the carbon emissions once the massive scale of hydrogen production and application takes place.

Should a carbon emission price be imposed on vehicles' emissions, say, at about $13/ton of CO_2 in the Beijing carbon emission exchange, the highest level among the regional exchanges in the PRC, we can calculate the real or social cost of FCEVs', BEVs', PHEVs', and ICEVs' carbon emissions, as Table 10 shows.

Table 10: Cost of Carbon Emissions by FCEVs, BEVs, PHEVs, and ICEVs
($/km)

	FCEVs (Pipeline Pathway)	BEVs	PHEVs	ICEVs
Passenger Cars	0.0005	0.0011	0.002	0.002
Buses	0.0044	0.0093	0.012	0.021
Trucks	0.0059	0.0091	0.012	0.016

Source: Authors' calculation.

According to Table 10, although the carbon emission costs of FCEVs are much lower than those of the alternatives, at the current levels of carbon prices, users can hardly notice the existence of the carbon cost when using conventional vehicles, since it is less than 1% of the TCO, even when imposing such a social cost of the externality. In other words, carbon prices need to increase by more than 10 times the current levels to make the environmental externality visible to users of vehicles.

5. CONCLUSIONS AND POLICY IMPLICATIONS

In this study, we examined the relationship between the energy prices and the feasibility of using hydrogen energy for road transport in the PRC, especially focusing on hydrogen as energy storage for renewables. We established a WTW model to analyze the total cost of supplying hydrogen refilling stations with hydrogen from renewable energy sources for vehicle use purposes. Subsequently, we built a TCO model to analyze the per kilometer cost of owning and using an FCEV compared with alternative powertrains, such as BEVs, PHEV/HEVs, and ICEVs.

We found that, compared with the current common retail hydrogen prices at hydrogen refilling stations operating in the PRC of around $12.2/kg, sourced from the purification of industrial byproduct hydrogen, hydrogen produced from all three sources of renewable energy and using pipelines, compressed hydrogen trucks, and LOHC trucks for delivery is competitive. However, the cost of hydrogen at such levels barely enables FCEVs as passenger cars to be economically competitive compared with vehicles with other powertrains given that both the central and the local government in the PRC provide substantial subsidies for the CAPEX of FCEVs. In the bus and truck fleet, FCEVs remain uncompetitive. In the case of FCEV buses, their TCO is about twice as high as that of conventional ICEV buses, while, in the case of FCEV trucks, their TCO is about three times as high as that of conventional ICEV trucks.

In our sensitivity analysis, with the cost of hydrogen varying in a range of 20% relative to the benchmark, we showed that it affects the competitiveness of FCEVs only marginally. Therefore, the high CAPEX of the FCEVs, rather than hydrogen as the fuel cost, is the main barrier to achieving competitiveness against alternative powertrains, especially in the case of the bus and truck fleets.

Our study thus shows that passenger FCEVs are already competitive against other alternative powertrains in the PRC. However, this depends on two critical conditions: 1. the generous subsidies for passenger FCEVs continue; 2. passenger FCEVs are available in the PRC at prices comparable to the models on sale in developed countries, such as Japan, the US, and Europe. In fact, most of the passenger FCEV models in the PRC are at the concept or prototype stage, and their costs are some twofold that of the Japanese models. It is thus recommendable to accelerate the development of the passenger FCEV supply chain in the PRC.

As regards the FCEVs for the bus and truck fleets, substantial gaps exist in terms of their TCO and therefore they are far from being competitive with alternative powertrains. We propose that policy makers should consider leveling up the subsidies that the government offers to FCEV buses and trucks while also expanding the support to intensify R&D in related technologies and supply chains.

So far, we have based our discussion on the competitiveness of hydrogen energy and its fuel cell application for the transport sector on the current policy framework and market mechanisms. We note that we have not included the economic value of the additional services that hydrogen provides to the power grid, such as load management, peak power supply, and energy storage services, since such mechanisms do not exist in the PRC yet. Accordingly, we propose that policy makers should consider developing such market mechanisms along with the pricing of carbon emissions that the PRC is developing to enhance the competitiveness of hydrogen energy further, especially encouraging its coupling with renewable energy capacities.

This study has focused on a hydrogen supply chain with the centralized production model. Future research should extend the scope to analyze the economic feasibility of a hydrogen supply chain with distributed production since distributed renewables, especially renewables integrated into the microgrid, are also developing fast globally and the PRC is likely to follow such developments in the future.

REFERENCES

Asia Pacific Energy Research Centre (APERC). 2018. *Perspectives on Hydrogenin the APEC Region*. Tokyo, June 2018.

China Hydrogen Alliance. 2018. "Research Report on the Development of Hydrogen Energy and Fuel Cell Industries in China" (in Chinese). Accessed 2 December 2019. http://www.h2cn.org/detail/449.html.

———. 2019. "White Paper on Hydrogen Energy and Fuel Cell Industries in China." Accessed 2 December 2019. http://www.h2cn.org/publicati/215.html.

Demir, Murat Emre, and Ibrahim Dincer. 2018. "Cost Assessment and Evaluation of Various Hydrogen Delivery Scenarios." *International Journal of Hydrogen Energy* 43, (22): 10420–30.

Department of Energy (US) (DOE). 2015. "Advancing Systems and Technologies to Produce Cleaner Fuels: Technology Assessments." Chapter 7 in *Quadrennial Technology Review 2015: An Assessment of Energy Technologies and Research Opportunities*. September 2015. Accessed 2 December 2019. https://www.energy.gov/sites/prod/files/2015/11/f27/QTR2015-7D-Hydrogen-Production-and-Delivery.pdf.

Economic Research Institute for ASEAN and East Asia (ERIA). 2019. "Demand and Supply Potential of Hydrogen Energy in East Asia." In *ERIA Research Project Report 2018*, No. 1, edited by Shigeru Kimura and Yanfei Li. Jakarta, May 2019.

FreedomCar and Fuel Partnership. 2009. *Hydrogen Production Roadmap: Technology Pathways to the Future*. Hydrogen Production Technical Team, United States, January 2009. DOI: 10.2172/1219571.

Fuel Cells and Hydrogen Joint Undertaking (FCH). 2019. *Hydrogen Roadmap Europe*. Belgium, January 2019.

Hassan, Aymane, Martin K. Patel, and David Parra. 2019. "An Assessment of the Impacts of Renewable and Conventional Electricity Supply on the Cost and Value of Power-to-Gas." *International Journal of Hydrogen Energy* 44 (19): 9577–93.

Hydrogen and Fuel Cell Strategy Council. 2019. *The Strategic Road Map for Hydrogen and Fuel Cells: Industry–Academia–Government Action Plan to Realize a "Hydrogen Society."* March 2019. Accessed 2 December 2019. https://www.meti.go.jp/english/press/2019/pdf/0312_002b.pdf.

Hydrogen Europe. 2018. *Hydrogen Enabling a Zero Emission Europe: Technology Roadmaps Full Pack*. September 2018. Accessed 2 December 2019. https://hydrogeneurope.eu.

International Energy Agency (IEA). 2019. *The Future of Hydrogen: Seizing Today's Opportunities*. June 2019. Paris: IEA.

James, B. D., D. A. DeSantis, and G. Saur. 2016. *Final Report: Hydrogen Production Pathways Cost Analysis (2013–2016)*. DOE Strategic Analysis 6231-1, U.S. Department of Energy, Office of Scientific and Technical Information United States, September 2019. DOI: 10.2172/1346418

Li, Y. 2019a. "Hydrogen May Be Key to ASEAN's Green Future." *China Daily*, 14 May 2019.

Li, Y. 2019b. "Hydrogen as a Clean Fuel for Transportation." *The ASEAN Post*, 7 October 2019.

Miller, M., A. S. K. Raju, and P. S. Roy. 2017. *The Development of Lifecycle Data for Hydrogen Fuel Production and Delivery*. UC Davis: National Center for Sustainable Transportation, October 2017. Accessed 2 December 2019. https://escholarship.org/uc/item/3pn8s961

Parra, David, Luis Valverde, F. Javier Pino, and Martin K. Patel. 2019. "A Review on the Role, Cost and Value of Hydrogen Energy Systems for Deep Decarbonisation." *Renewable and Sustainable Energy Reviews* 101: 279–94.

Pereira, S. R., and M. C. Coelho. 2013. "Life Cycle Analysis of Hydrogen—A Well-to-Wheels Analysis for Portugal." *International Journal of Hydrogen Energy* 38 (5): 2029–38. doi:https://doi.org/10.1016/j.ijhydene.2012.12.029.

Rahil, A. 2017. "Dispatchable Hydrogen Production at the Forecourt for Electricity Demand Shaping." *Sustainability* 9: 1785.

Rahil, A., R. Gammon, and N. Brown. 2018. "Techno-economic Assessment of Dispatchable Hydrogen Production by Multiple Electrolysers in Libya." *Journal of Energy Storage* 16: 46–60.

Reuß, M., T. Grube, M. Robinius, and D. Stolten. 2019. "A Hydrogen Supply Chain with Spatial Resolution: Comparative Analysis of Infrastructure Technologies in Germany." *Applied Energy* 247: 438–53.

Reuß, M., T. Grube, M. Robinius, P. Preuster, P. Wasserscheid, and D. Stolten. 2017. "Seasonal Storage and Alternative Carriers: A Flexible Hydrogen Supply Chain Model." *Applied Energy* 200: 290–302.

Teichmann, Daniel, Wolfgang Arlt, and Peter Wasserscheid. 2012. "Liquid Organic Hydrogen Carriers as an Efficient Vector for the Transport and Storage of Renewable Energy." *International Journal of Hydrogen Energy* 37 (23): 18118–32.